

**INTELLIGENT PLANNING AND SCHEDULING FOR  
CONTROLLED LIFE SUPPORT SYSTEMS**

**Final Report  
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## **ABSTRACT**

Planning in Controlled Ecological Life Support Systems (CELSS) requires special lookahead capabilities due to the complex and long-term dynamic behavior of biological systems. This project characterizes the behavior of CELSS, identifies the requirements of intelligent planning systems for CELSS, proposes the decomposition of the planning task into short-term and long-term planning, and studies the crop scheduling problem as an initial approach to long-term planning.

CELSS is studied in the realm of Chaos. The amount of biomass in the system is modeled using a bounded quadratic iterator. The results suggests that closed ecological systems can exhibit periodic behavior when imposed external or artificial control.

The main characteristics of CELSS from the planning and scheduling perspective are discussed and requirements for planning systems are given. Crop scheduling problem is identified as an important component of the required long-term lookahead capabilities of a CELSS planner. The main characteristics of crop scheduling are described and a model is proposed to represent the problem. A surrogate measure of the probability of survival is developed. The measure reflects the absolute deviation of the vital reservoir levels from their nominal values. The solution space is generated using a probability distribution which captures both knowledge about the system and the current state of affairs at each decision epoch. This probability distribution is used in the context of an evolution paradigm.

The concepts developed serve as the basis for the development of a simple crop scheduling tool which is used to demonstrate its usefulness in the design and operation of CELSS.

## INTRODUCTION

Significant automation will be required for the operation of Controlled Ecological Life Support Systems (CELSS) in order to enable the crew to spend more time carrying out science and mission related activities rather than routine, but indispensable, life support related activities. The successful control of a CELSS will depend to a great extent on our ability to predict the behavior of highly restrained biological systems and to maintain stable balance between the crew, biological, mechanical and physico-chemical systems.

Long-term dynamic and non-linear behavior characterize ecological systems. For instance, the sole decision of planting a given crop today must be associated with a series of activities and events which will both produce and consume vital resources for a period of time measurable in months or years. More over, the appropriateness of a planting decision depends on what the current state of affairs is - i.e., what other crops are currently in growth, what are the  $O_2$ ,  $CO_2$ , and food storage levels, energy status, etc. Managing and controlling this type of system present a formidable task which may be impossible to deal with manually.

This project studies issues associated with intelligent planning and scheduling as means to aid in the design, operation and behavior prediction of CELSS. This report will present the planning and scheduling models and methodologies developed during the summer program. The implementation of a crop scheduling tool using these concepts is presented in a separated report in this volume (Whitaker and Leon, 1995).

Given a set of goals, a set of allowable actions, and an a description of an initial state of affairs, *planning* is defined as the task of finding a sequence of actions that will bring about a state of affairs in which all the desired goals are satisfied (Kautz and Pednault, 1988). *Scheduling* is defined here as the resolution of time conflicts generated by actions competing for scarce resources. It must be noted that, planning can also assign resources to actions; however, time conflicts on the usage of resources is only partially specified in the form of precedence relations between actions. On the other side, scheduling assumes that the sequence of actions required to accomplish a given goal is given in advance and only deals with the appropriate timing between these actions. It is well known that most practical cases of planning and scheduling problems are very complex problems proven to be mathematically intractable from the optimization or satisficing point of view. Figure 1 illustrates a sample plan generated to accomplish the goal "harvest wheat at time 1 and plant lettuce at time 2." The plan will also specify resource assignment to action. For instance, "crew person No.2" is assigned to perform the action "select seeds."

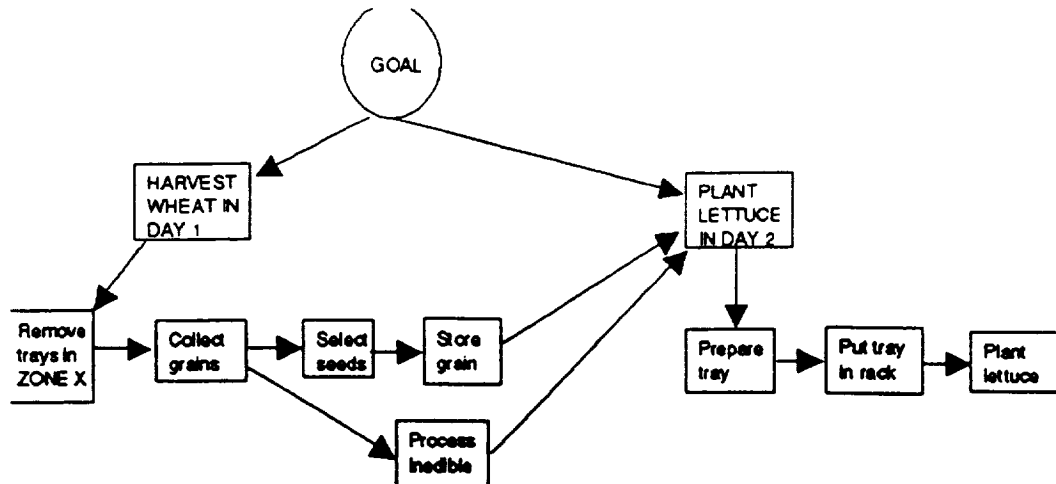


Figure 1. A typical plan

### CHARACTERISTICS OF CELSS

From the planning, scheduling and control perspective, the inclusion of biological systems is what makes CELSS unique when compared to most systems studied in the literature. Species in biological systems adapt to changes in the environments using their internal mechanisms of control. In fact, it has been suggested that species may adopt the strategy of instability in order to enhance their chances of survival (Colombano, 1981). Thus, it may not be appropriate to equate stability with survival. Another complicating fact is that, biological systems can be controlled through the careful manipulation of external environmental variables; however, the relation between the control action and the systems's response can be very indirect, subject to extensive filtering and occasional reinterpretation (MacElroy, 1981). Simple CELSS models have been used to demonstrate that it is possible that failures can occur at times long after the cause of the perturbation has been removed (Auslander, 1981). For instance, it is possible that the percent of edible biomass obtained from a given crop can be severely decreased if at some point during growth the plants were subjected to long periods of darkness. In this example, the time elapsed between the disturbance (i.e., darkness) and the effect (i.e., harvest) can be in the order of months or several weeks.

The above characteristics make the design and operation of CELSS a formidable challenge which we are only starting to understand. Among the unanswered questions there are those related to the amount of local versus global control required, the quantification of the probability of survival, the sizing of vital element reservoirs, and

others. New paradigms may be necessary to model and analyze these systems. In this project, we explored two of a number of possible paradigms. Specifically, *Chaos* was used to model the non-linear and dynamic behavior of the system, and *Evolution* is used as a paradigm to generate a space of crop schedules.

### CELSS - A Perspective From Chaos

A main difference between "natural" or "free" biological systems and CELSS resides in the latter's imposition of external bounds on the system's response. In this section we describe how Chaos theory can be used to study the response of biological systems (i.e., amount of biomass) when bounded externally. A simple experiment demonstrates that an unstable "free" biological system may have a periodic behavior when "constrained" externally.

Chaos theory has been recently used to model population dynamics and the behavior of biological and other natural systems (May, 1976). Chaotic behavior can be represented by simple mathematical models - however, the resulting behavior may be unpredictable. Chaos can be used to model the behavior of systems that are non-linear and sensitive to initial conditions. Non-linearity implies that what occurs now significantly affects future events. As with biological behavior, chaotic behavior is a collection of many orderly behaviors, none of which dominates each other under ordinary circumstances. The explicit consideration of this apparent instability in systems behavior may enable the development of better models for the analysis and synthesis of a controlled system. For instance, chaotic systems have been controlled by perturbing them in the right way so they will be forced to follow a different behavior. Furthermore, these controllers have proved to be more efficient than their traditional counterparts.

The quadratic iterator known as the Logistic Function (Velhurst, 1984) is used in the experiments. This function can be expressed as follows:

$$x(n+1) = a x(n) (1 - x(n))$$

Where,  $x(n)$  is the normalized size of the population of a species at time  $n$ , and  $a$  is a proportionality constant. This function has interesting characteristics, such as:

1. The size of the population at any time depends on the initial condition ( $x(0)$ ).
2. Stable, periodic or unstable behavior can be represented with the appropriate choice of the parameter  $a$ .
3. It can portray abrupt changes in behavior from order to chaos - i.e., period-doubling bifurcations.
4. It can portray long-term stability through "attracting" states.
5. It exhibits "universal" behavior observed in many natural systems.

These characteristics make the apparently random behavior of the systems predictable to some extent. The important result is that this predictability allows for the control of chaotic systems; in fact, there is evidence that control using Chaos can outperform traditional control (Ditto and Pecora, 1993).

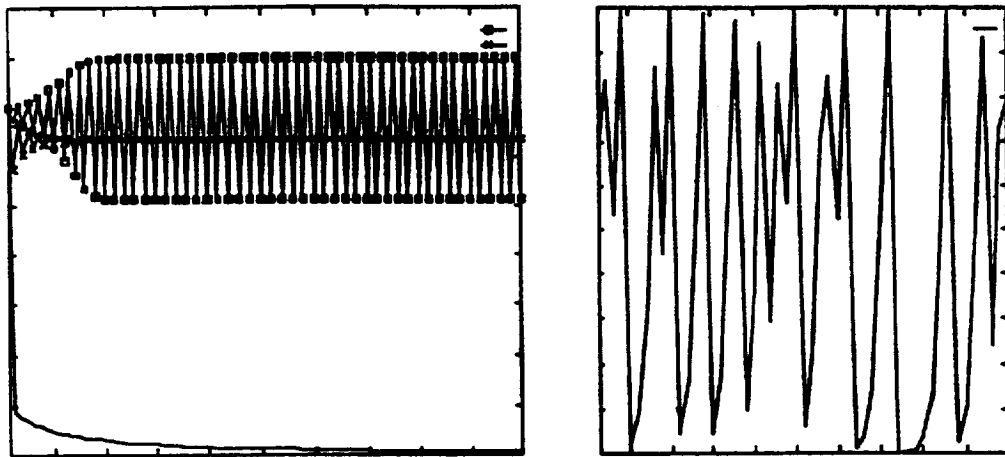
Figure 2 (a), (b) and (c) show plots of the same function for different values of  $a$  resulting in stable, periodic and unstable behavior, respectively.

We model a CELSS using the logistic function; where,  $x(n)$  represents the amount of plant biomass in the system. Clearly, in a CELSS this amount cannot grow unbounded. In order to model this, an upper bound,  $U$ , is imposed limiting the maximum amount of biomass at any point in time. The function used in the experiment is modified as follows:

$$x(n+1) = a x(n) (1 - x(n))$$

if  $x(n+1) > U$ , then set  $x(n+1) = U$ .

The value of  $a=4.0$  applied to the original "free" system yields the unstable behavior depicted in Figure 2(b). However, the behavior of the "bounded" system became periodic as illustrated in Figure 3.



(a) Extinction, stable and periodic

(c) Unstable,  $a = 4.0$

Figure 2 .The Logistic Function

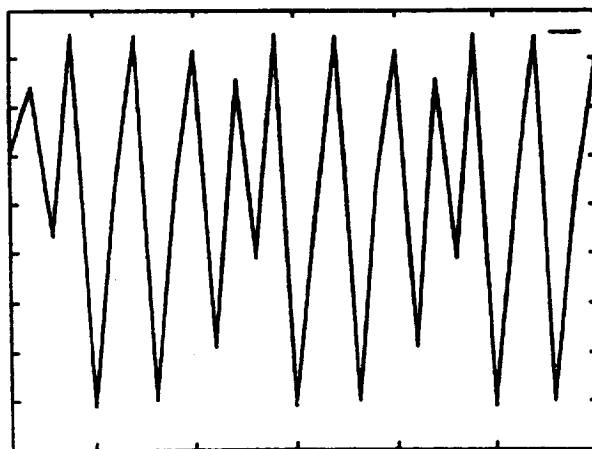


Figure 3. A bounded Logistic function with  $a = 4.0$ ,  $U=0.9$

This interesting result using a simple experiment suggests that the implementation of a CELSS may be possible. Further, it suggests that the system will have alternating periods of time in which the biological system is mostly controlled using the plant's internal control mechanisms and period during which artificial control will be needed. For instance, incineration or other recycling process may be required whenever the amount of food produced is excessive.

This simple experiment also suggests that more formal and thorough studies using the Chaos paradigm may be valuable for the understanding of CELSS.

## **CELSS PLANNERS - REQUIREMENTS**

The long duration of CELSS operations and the complex dynamics induced by the biological systems, mechanical reliability and information uncertainty make it necessary for a CELSS planner to have the following special requirements:

1. Planners must explicitly consider the long-term dynamics (i.e., in the order of several months) inherent to biological systems. This implies the need of lookahead capabilities not present in traditional planners. The lookahead should ensure long-term system stability and strategic management of resources. Only vital resources must be considered and time granularity should be in the order of days.
2. Detail resource scheduling and minute-to-minute planning should be done using a planning horizon in the order of hours to days. It is important that detailed plans are consistent with the long-term lookahead analysis.
3. Planners must exploit the intelligence and flexibility of humans. This implies that planners should: (a) enable the incorporation of user input before and during plan generation, (b) provide with plan explanation and (c) provide with "what-if" analysis capabilities.
4. Planners must be adaptable to unforeseen changes in operating conditions. CELSS may need to operate in isolation from terrestrial feedback for months. The planner must be able to accommodate to unknown or unforeseen conditions during the design of the system. Planners must allow the incorporation of experience for adaptation to new conditions and improvement in performance.

## **PLANNING PROBLEM DECOMPOSITION**

The requirements described above suggest the decomposition of the planning problem into two subproblem: Long-Term Planning (LTP) and Short-Term Planning (STP). Figure 4 depicts the proposed problem decomposition. STP is much like most planning problems in the literature; i.e., is well described by the definition of planning in the beginning of this report. Although very important, this will not be discussed further in this report.

The LTP can be described as the problem of scheduling strategic resources. Strategic resources may include crew, crops, main elements ( $O_2$ ,  $CO_2$ ,  $H_2O$ , etc.), food, storage space and others. Figure 4 shows how only the initial portion of a long-term plan is broken down into further detail in the short-term plan. Further, it

also suggests that the immediate actions prescribed by LTP ensure the adequate levels in the long run. It must be noted that LTP gives the planning tool with predictive capabilities which make it also useful as a "what-if" tool for design and situation diagnosis.

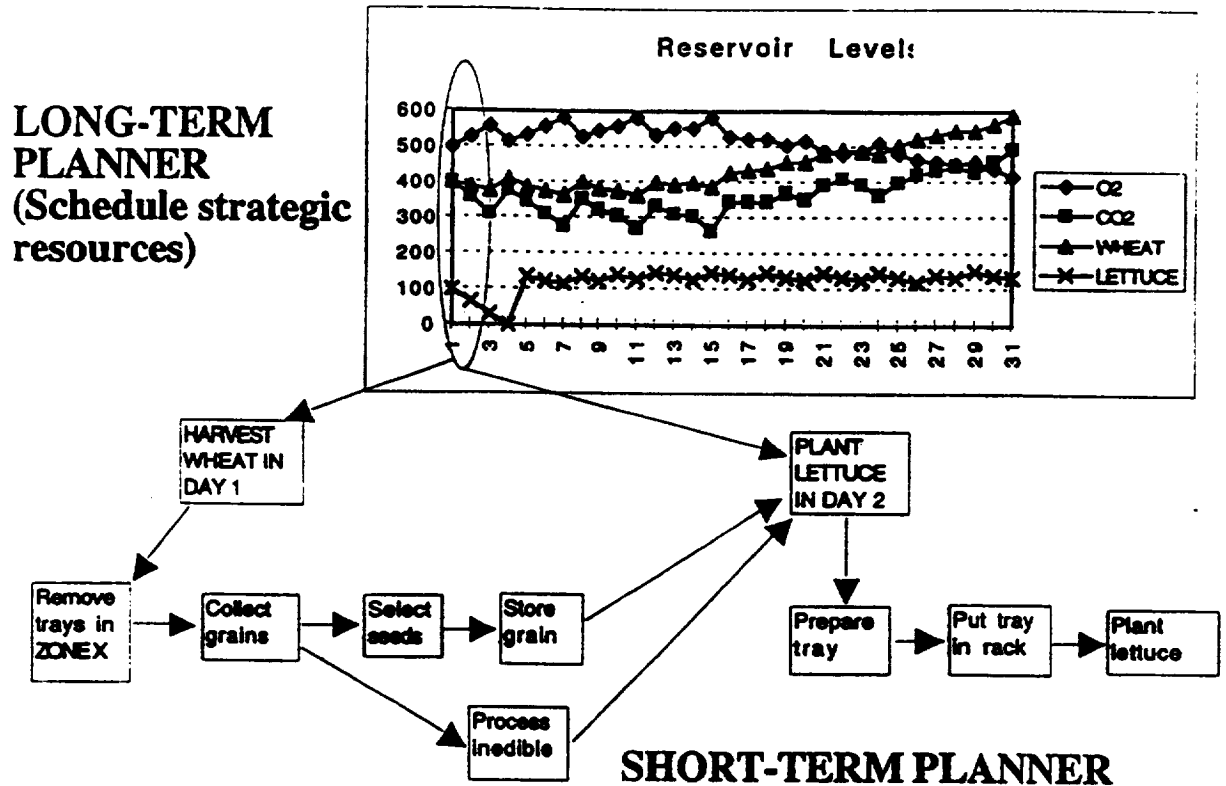


Figure 4. Planning problem decomposition

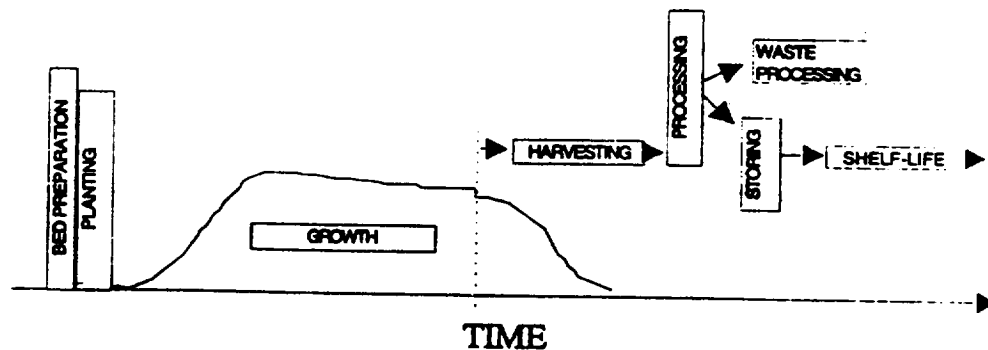
### THE CROP SCHEDULING PROBLEM

The crew, crops and other live agents determine to a great extent the long-term behavior of a CELSS. In this project, a first look is given to the Crop Scheduling Problem (CSP). CSP can be formulated as follows:

#### CSP:

Decision Variables:	What, how much and when to plant.
Objective:	Maximize the probability of survival.
Constraints:	Conservation and transformation of mass
	Crew availability
	Space availability (planting, process, storage)
	Energy and other operational constraints

This scheduling problem is unique for a number of reasons which make it specially challenging when compared with more traditional scheduling problems. The first distinction is related to the time characteristics of plants as illustrated in Figure 5. Once a decision of planting is made, this triggers a several events in the near (same day) and far (months later) future. Although some precedence exists between these events, some partial sequences may occur simultaneously and may require of the same scarce resources. The management of such a system becomes too complicated to deal with manually, specially if different types of crops are considered. For instance in Figure 5, at the time of planting one must consider how will this affect the  $O_2$  and  $CO_2$  reservoirs during its growth and how will it impact the food storage space, crew loading and waste processing about 3 months later (e.g., wheat). The non-linearity of the problem becomes evident when observing that other planting decisions will have to be made while the events triggered by the decision of planting are still taking place.



**Figure 5. A plant model**

### **A CROP SCHEDULING MODEL**

In this section a model for CSP is proposed. First, a surrogate measure of the probability of survival is proposed as an objective function. Second, a solution space that is generated using an evolution paradigm is described. Finally, the search and ideas to deal with the size of the solution space will be discussed.

#### **Objective Function**

The quantification of the probability of survival is not a trivial issue. This problem is similar to the one in safety analysis but in CELSS is complicated by the long-term dynamics inherent to such systems as growing plants (Auslander, 1981). Here, the probability of survival is represented using a surrogate measure,  $Z$ , which reflects the absolute deviations of the each vital reservoir's level from the corresponding nominal value.

Let  $d_r$  be some normalized indicator (i.e., between 0 and 1) of the average deviation of reservoir's  $r$  level from its nominal value.  $Z$  can be defined as

$$Z = f(d_1, d_2, \dots, d_R)$$

where,  $R$  is the total number of vital reservoirs and  $f(.)$  is an appropriate real valued function.

### **Solution Space**

The state of the system is defined by the status of the in-growth crops, number of empty trays and reservoir levels. Other important information are the time at which the state is described, crew profile, human model, plant models and physical system models.

At a decision epoch, a decision is made as for what, how much and when to plant. Decision epochs are prompted by significant events. These events can be classified into (i) biological events, (ii) user specified events and (iii) stochastic events.

The solution space can be represented as a tree where the nodes are decision points and the branches are different paths resulting from different scheduling decisions. A path in this tree will represent one possible schedule. A schedule which satisfies all the operating constraints is termed an admissible plan. The scheduling problem can be stated as the problem of finding the admissible plan which minimizes  $Z$ .

Considering all possible alternatives at each decision epoch would be impractical. Rather, we suggest the generation of alternatives using heuristics which capture both knowledge about the problem, as well as, the current state of affairs. Inspired by evolution processes, a fitness probability distribution is determined at each decision epoch. The random variable is the crop type, and the corresponding probability reflects the marginal effect that planting the corresponding crop will have on the vital reservoirs. These probabilities can be computed using arguments similar to the ones used in the determination of the objective function. Knowledge about the process is captured through the use of the system's models to predict the impact that each crop would have if planted. The current state of affairs is captured since the reservoir levels at the decision epoch must be considered. It must be noted that this probability distribution must be computed at each decision epoch to reflect the updated "desirability" of each crop. Thus the term *desirability probability*.

There are several different ways that this probability can be used to generate the solution space. The most efficient way of using it is still a matter of further research. One way to implement this generation strategy is illustrated in Figure 6. Given a number of empty trays, one can randomly sample from the desirability distribution until all empty trays are filled - noted that, *plant-nothing* is considered as one possible crop. Figure 6 illustrates how a single path (schedule) can be generated.

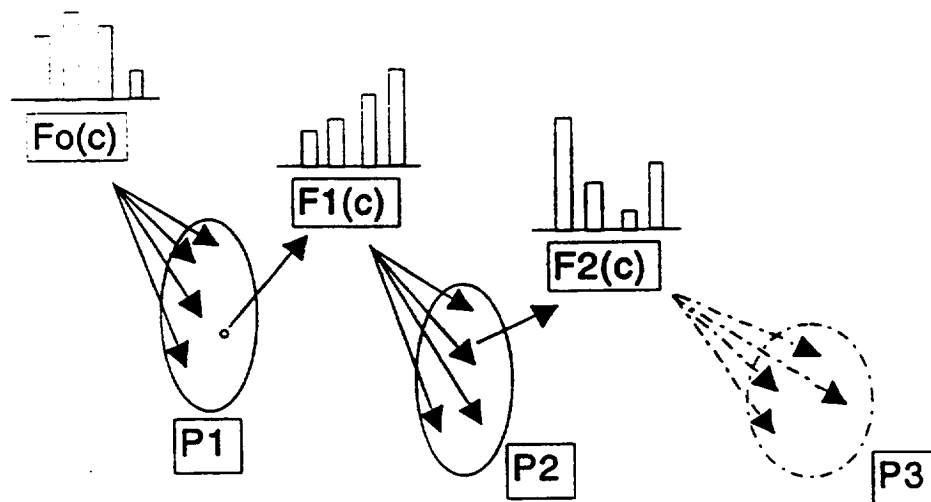
### **Search and Dealing With Complexity**

Clearly, generating the space using local information will unavoidably lead to the necessity of backtracking when non-admissible situations are encountered. Too

much backtracking may render the approach impractical. In the case of CELSS, however, too much backtracking may suggest that the system is not robust enough; i.e., there are only a few paths leading to mission completion. If this is the case, a system redesign will be more recommendable than a more sophisticated scheduler. Clearly, too much backtracking may also suggest a poor space generation scheme.

For CELSS it would be desirable to allow for user intervention if conflicts cannot be resolved automatically. Hence, the importance of schedule explanation to aid the user in suggesting conflict resolution.

Most existing search strategies may be applied to deal with the size of the solution space. The determination of the most appropriate search strategy is still an open research issue.



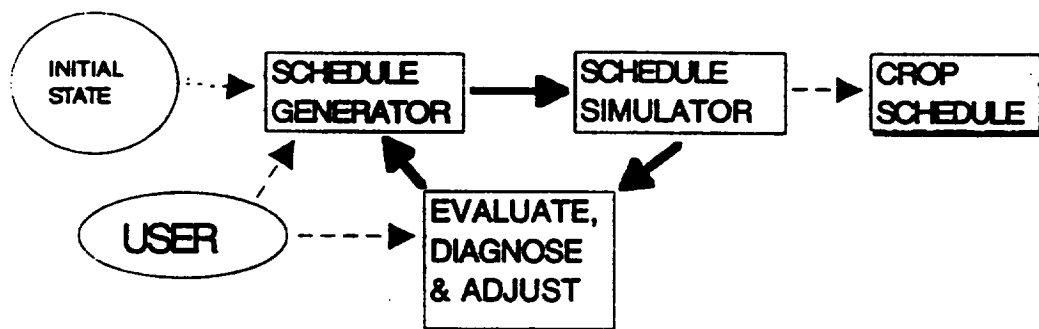
**Figure 6. An evolution approach**

### **AN EXAMPLE IMPLEMENTATION OF THE A SCHEDULER**

A simple crop scheduler was implemented to illustrate its potential use in planning as well as design of CELSS. A detailed description of this implementation is contained in a separate report (Whitaker and Leon, 1995). Figure 7 illustrates the main components of the Intelligent Crop Scheduler (ICS) developed during this summer project. ICS has two main components: a Schedule Generator (SG) and a

Schedule Simulator (SS). SG is based on the concepts described above. SS contains detail human metabolic simulator and two plant models (i.e., wheat and lettuce). It also contains a simplified physical system model as illustrated in Figure 8. For simplicity, only  $O_2$ ,  $CO_2$ , edible wheat and edible lettuce reservoirs are considered. The main systems considered are the crew, plants and a generic waste processing system.

A sample planting schedule is illustrated in Figure 9. Figure 10 illustrates the reservoir levels for the schedule, as well as, its performance. A variety a scenarios were run illustrating how the output can be used to aid in sizing the gas tanks, food storage space, growing area, crew profile, planting strategy, growing parameters, and others. See Whitaker and Leon (1995) for a discussion of the example cases.



**Figure 7. Intelligent Crop Scheduler**

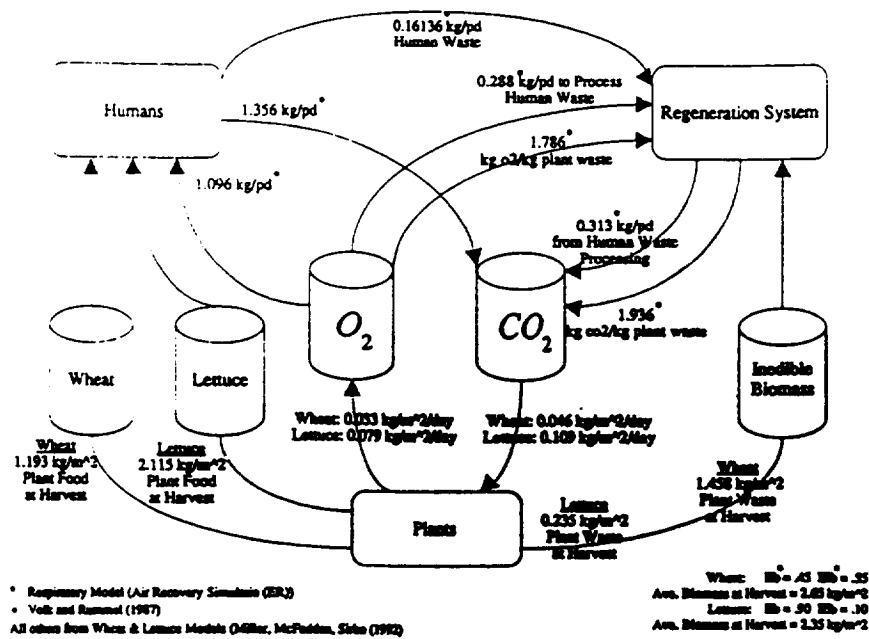


Figure 8. A simplified CELSS model

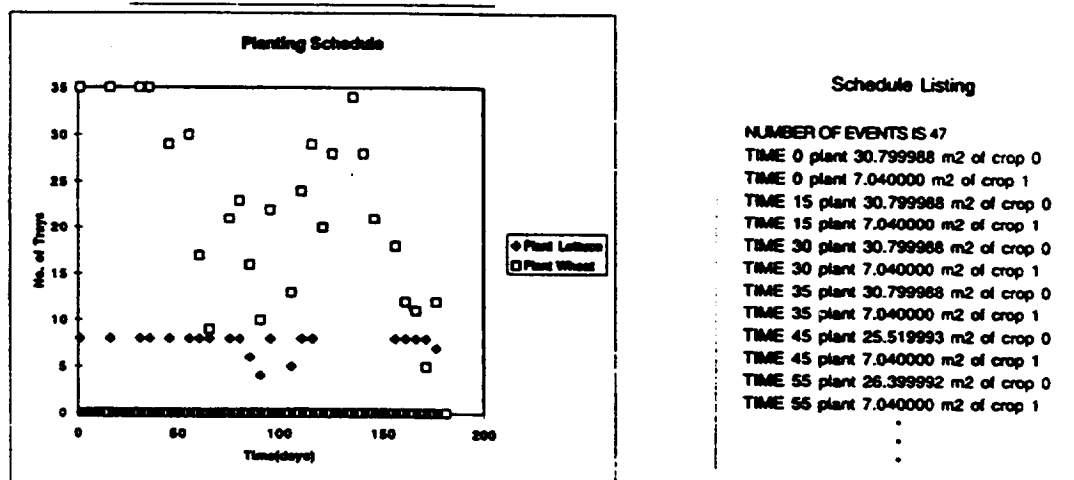


Figure 9. Sample crop schedule

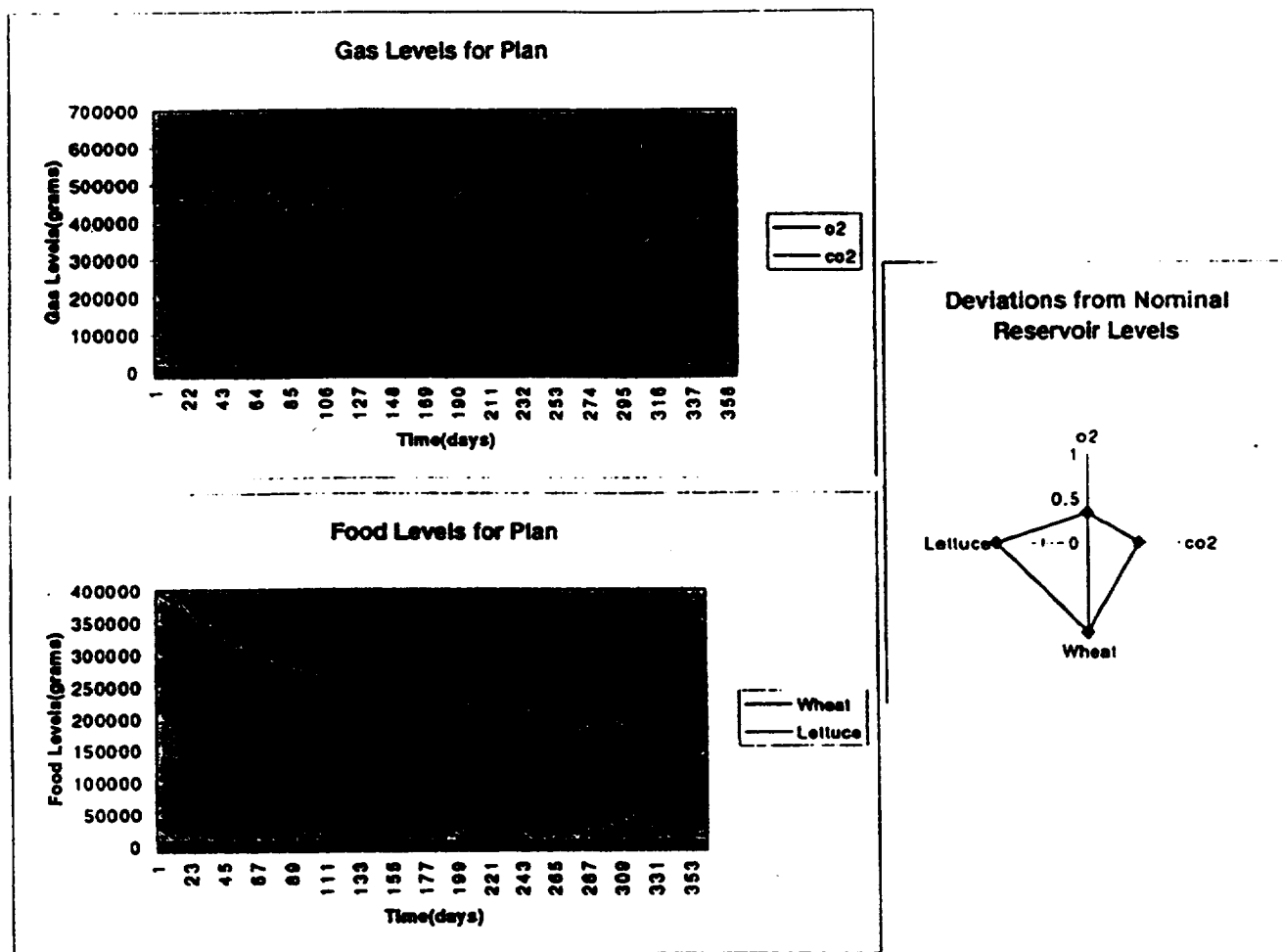


Figure 10. Sample reservoir level output

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